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Simulating the Acquisition of Verb Inflection in Typically Developing Children and Children With Developmental Language Disorder in English and Spanish

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Abstract

Children with developmental language disorder (DLD) have significant deficits in language ability that cannot be attributed to neurological damage, hearing impairment, or intellectual disability. The symptoms displayed by children with DLD differ across languages. In English, DLD is often marked by severe difficulties acquiring verb inflection. Such difficulties are less apparent in languages with rich verb morphology like Spanish and Italian. Here we show how these differential profiles can be understood in terms of an interaction between properties of the input language, and the child's ability to learn predictive relations between linguistic elements that are separated within a sentence. We apply a simple associative learning model to sequential English and Spanish stimuli and show how the model's ability to associate cues occurring earlier in time with later outcomes affects the acquisition of verb inflection in English more than in Spanish. We relate this to the high frequency of the English bare form (which acts as a default) and the English process of question formation, which means that (unlike in Spanish) bare forms frequently occur in third-person singular contexts. Finally, we hypothesize that the pro-drop nature of Spanish makes it easier to associate person and number cues with the verb inflection than in English. Since the factors that conspire to make English verb inflection particularly challenging for learners with weak sequential learning abilities are much reduced or absent in Spanish, this provides an explanation for why learning Spanish verb inflection is relatively unaffected in children with DLD.

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1. Introduction

A major challenge in the study of language acquisition is to develop theories and models that can account not only for data from different languages but also for differences between typically developing and clinical populations. This is particularly true in the area of verb inflection, which shows considerable variation across languages, both in terms of the complexity of the paradigm and the time that it takes children to master it. Spanish, for example, uses a different verb form for each of the six present-tense person–number combinations, compared to only two in English (the bare form and third-person singular -s). However, despite its greater apparent complexity, children are quicker to acquire Spanish than English verb inflection. Rice, Wexler, and Hershberger (1998) present data showing that typically developing English-speaking children only reach 90% correct provision of third-person singular -s when they are around 4.5 years old. Before this time, they tend to produce *Optional Infinitive* errors: bare or untensed forms (e.g., *go*), in situations where a third-person singular form (e.g., *goes*) is required in the adult grammar. By contrast, Hoekstra and Hyams (1998) report error rates lower than 5% in Spanish-speaking children under 2.5 years old. While these low overall error rates hide higher error rates in low-frequency parts of the system (Aguado-Orea & Pine, 2015), error rates for high-frequency forms are considerably lower than for English third-person singular.

This relative ease of acquisition of Spanish verb inflection extends to clinical populations. One such population is the group of children with developmental language disorder (DLD), often referred to in the research literature as children with specific language impairment (SLI). Children with DLD are slow to acquire language and may lag several years behind their typically developing peers. Yet the cause of DLD is largely unknown. These children show normal hearing, no evidence of neurological damage or disease, and they do not exhibit the symptoms associated with autism spectrum disorder. Nonverbal intelligence is safely above the level of intellectual disability. Although genetic factors appear to be involved in DLD, molecular genetic studies have not uncovered a consistent mutation or variant that explains the disorder. Instead, DLD seems to have a multifactorial basis, with contributions from combinations of genes as well as environmental factors (see Leonard, 2014 for a review).

Given the multifactorial nature of DLD, it is not surprising that there is heterogeneity in this population. Some children with DLD show subtle weaknesses in developmental areas outside of language, and the language symptoms themselves are not identical across children with this diagnosis. Yet, despite this heterogeneity, there are common profiles of linguistic strengths and weaknesses within each language. In English, a very common profile is a mild to moderate deficit in vocabulary and phonology, with a more striking deficit in the area of morphosyntax. Within morphosyntax, problems with verb morphology are usually the most severe. These problems persist for far longer than in typically developing children, even when controlling for factors such as mean length of utterance (MLU) and size of verb inventory (e.g., Leonard, Eyer, Bedore, & Grela, 1997; Leonard, Miller, & Gerber, 1999). In contrast, verb inflection in Spanish-speaking children with DLD is relatively unaffected, and children perform at levels comparable to MLU-matched controls—though not necessarily age-matched controls (Bedore & Leonard, 2001).

1.1. Three accounts of cross-linguistic differences in verb inflection

Several explanations have been put forward for the cross-linguistic differences in the acquisition of verb inflection in typically developing children and children with DLD. According to one class of accounts, formal differences between the grammars of English and Spanish interact with maturational aspects of the child's representation of the target grammar to account for the different profiles (Rice, Noll, & Grimm, 1997; Wexler, 1994, 1998). Such accounts place the nature of the deficit in DLD within the child's grammar.

A second class of accounts places more emphasis on the role of input. These accounts assume that characteristics of each language will make some linguistic details more difficult than others, and these details will vary according to the language. For children with DLD, these fragile details will be especially problematic and will lead to the exaggerated grammatical profiles seen for these children (Leonard, 2014). For example, according to the *morphological richness* account, children with DLD will gravitate toward the most prevalent grammatical cues in the language, often at the expense of more subtle grammatical information (Bedore & Leonard, 2001; Kunnari et al., 2011). In a language like English, these children will devote their linguistic resources to the dominant cues of word order, whereas children who learn a language with a rich verb inflection system such as Spanish will devote their resources to this area of grammar.

When children are already weak in their language ability, the tendency to focus almost exclusively on dominant cues can compound the problem. For example, according to the competing sources of input (CSI) approach (Fey, Leonard, Bredin-Oja, & Deevy, 2017; Leonard & Deevy, 2011; Leonard, Fey, Deevy, & Bredin-Oja, 2015), errors such as *She like puppies* alternate with correct versions in the speech of children with DLD because in input such as *Does she like milk?*, the children may not grasp the relation between the separated elements *does* and *like* and are drawn instead to the meaningful and seemingly well-ordered sequence *she like milk*. Other types of input can lead to similar incorrect interpretations, as in *Let's watch the boy kick the ball*, where the local sequence *the boy kick the ball* is well ordered but permissible only because of the earlier appearing (perception) verb, *watch*. In English, the bare forms *like* and *kick* are infinitives but are phonetically identical to the "zero-marked" finite forms seen in *I like*, *you like*, *we like*, and *they like*, which might further induce children to use *she like milk* and *the boy kick the ball* as stand-alone utterances.

In contrast, in a language with a rich verb inflection system such as Spanish, children with DLD will rely more on inflections. Furthermore, Spanish does not employ the equivalent of fronted auxiliaries to form questions which, in English, create local sequences such as *boy kick the ball*. Instead, in Spanish, the main verb *kick* would be inflected in the same way as in declaratives.

Approaches such as the morphological richness account and the CSI account do not explain the language disorder itself. They only offer proposals for how a general weakness in language learning will translate into a particular profile given the input characteristics of the language. For example, children's weaknesses could be in not understanding the linguistic principle of nonlocal dependency relations or there may be a more general problem such as a working memory deficit. In both cases, meaningful local sequences such as *she like milk* would be a lure because earlier material in the input sentence was not considered.

A third class of accounts posits that cross-linguistic differences in the acquisition of verb inflection reflect the interaction between more general learning processes and the statistical properties of the input. Such accounts are compatible with recent modeling work showing that cross-linguistic differences in the acquisition of verb inflection by typically developing children can be understood in terms of input-driven learning (Freudenthal, Pine, Aguado-Orea, & Gobet, 2007; Freudenthal, Pine, & Gobet, 2010; Freudenthal, Pine, Jones, & Gobet, 2015a, 2015b) and focus on DLD as a type of cognitive deficit that affects language development. Indeed, there is a growing body of evidence indicating that many children with DLD display subtle cognitive deficits—evidence that has contributed to the view that DLD may be a more appropriate label than SLI for these children (Bishop, Snowling, Thompson, Greenhalgh, & CATALISE 2 consortium, 2017). In particular, children with DLD have been shown to perform below typically developing peers on tests of working memory (Archibald & Gathercole, 2006; Ellis Weismer, 1996), nonword repetition (Bishop, North, & Donlan, 1996; Ellis Weismer et al., 2000), and sentence repetition (Conti-Ramsden, Botting, & Faragher, 2001). Although many of these tests involve language, they place particular demands on the ability to retain sequences of elements. Recent meta-analyses further suggest a particular problem with the learning of sequential information (verbal statistical learning: Lammertink, Boersma, Wijnen, & Rispens, 2017; serial reaction time tasks: Lum, Conti-Ramsden, Morgan, & Ullman, 2014).

In this paper, we pursue this third approach. We will show that the structure and statistics of English and Spanish differ in important ways that make the English system of verb inflection more difficult to learn. We do so by training a computational model of sequential learning that uses prediction error to identify the cues relevant to correct inflectional marking. We use the model, which associates person–number cues as well as sentence-level cues with target verb inflections, to investigate how the structure and statistics of the input, as well as the model's ability to discriminate the cues appropriate to a set of inflectional outcomes, affect its performance.

The DLD weakness with verb inflections in our approach is operationalized as difficulty with related material that is separated in a sentence. More specifically, we suggest that children with DLD have difficulty learning the predictive relationships that exist between stimuli (words) in sequences that unfold over time. Note that we are rather agnostic regarding the precise nature of this deficit. Difficulty identifying these relationships may reflect a pure sequential learning deficit, but they may equally well reflect problems in working memory, auditory processing, or some other type of deficit that affects the processing of sequential information. Indeed, the multifaceted nature of DLD may well reflect a range of deficits that affect the learning of sequential information in subtly different ways. However, we will show in this paper that an impaired ability to learn sequential information is likely to affect the acquisition of verb inflection in English far more than it will in Spanish. In the next section we will describe important differences between Spanish and English and their relevance to DLD, before going on to describe our (sequential) learning model.

1.2. Relevant differences between Spanish and English

Spanish and English differ in a number of ways that result in Spanish input providing far more evidence for verb inflection than English input. Here we focus on three major differences. First, the Spanish inflectional paradigm uses a different form for all present-tense, person–number combinations, compared to only two (the bare form and third singular -s) for English. Second, the English process of question formation means that, unlike in Spanish, bare forms frequently occur in third singular contexts (*Does he run?*). Third, because Spanish is a pro-drop language, overt subjects are optional, and subjecthood could be argued to be expressed by the verb inflection. In contrast, overt subjects are obligatory in English and are expressed using a (pro)noun which is separated from the verb. We discuss these differences and how they might be affected by sequential learning abilities below.

1.2.1. Differences in paradigm complexity

Spanish has six different present-tense forms—one for every person–number combination. In contrast, English uses only one overtly inflected form (the third-person singular) with the other five forms matching the infinitive or bare form (which is also used in frequent modal constructions, e.g., *He can go*). As a result, the frequency of the English bare form far outweighs that of the third-person singular for the vast majority of lexical verbs. This property of English may lead children acquiring the language to treat the bare form as a default, which is used instead of the third-person singular. Evidence for this hypothesis is provided by Räsänen, Ambridge, and Pine (2014), who elicited third-person singular verb forms from English-speaking children and found that, across the 48 verbs used, the rate of bare forms in the input (i.e., *eat* vs. *eats*) was the best predictor of children's production of bare forms in third-person singular contexts. Defaulting effects have also been reported in other, more highly inflected languages such as Finnish (Laalo, 2003; Toivainen, 1980) and Spanish (Aguado-Orea & Pine, 2015; Radford & Ploenning-Pacheco, 1995), where the most frequent form is different from the infinitive. Aguado-Orea and Pine report data from two Spanish-speaking children who produce the most frequent tensed form (third-person singular present) in contexts where a less frequent form (e.g., third-person plural present) is required. Defaulting errors are thus not restricted to English. However, the impoverished nature of English verb inflection means that defaulting effects are likely to be more pervasive in English than in other languages.

Evidence for defaulting effects in English DLD is provided by Kueser, Leonard, and Deevy (2017), who replicate the findings of Räsänen et al., but find that children with DLD produce more bare forms than typically developing children, thus raising the possibility that defaulting effects are stronger in children with DLD. Bedore and Leonard (2001) find that Spanish children with DLD do produce more errors than age-matched (but not MLU-matched) controls. The most common error is the production of a third-person singular form as a substitute for the correct inflected form, a finding that is consistent with the reports of Aguado-Orea and Pine (2015), and suggests that defaulting effects may persist for longer in children with DLD.

1.2.2. Differences in question formation

A second challenge for children acquiring English is that third-person singular subjects are frequently paired with bare or infinitive forms in the input. Unlike in Spanish, where (polar) questions normally only differ from declaratives in intonation contour (and thus provide evidence for inflection on the main verb), English questions are formed through the inversion of the subject and modal/auxiliary verb (e.g., *Can he go?*) or through the use of dummy auxiliary *do* (e.g., *Does he go?*). English questions thus provide a model for phrases like *he go* and may lead children to (incorrectly) infer that such phrases are permissible in isolation. Evidence for such an account is provided by Theakston, Lieven, and Tomasello (2003), who showed that children are more likely to produce a novel verb in a nonfinite form (e.g., *It mib*), after hearing it exclusively in questions (e.g., *Does it mib?*), rather than declaratives (*Look, it mibs*) or a mix of questions and declaratives (*Does it mib? Look, it mibs*).

As noted earlier, the idea that English question formation may pose problems for (both typically developing and language-impaired) children is formalized in the CSI hypothesis which states that children extract nonfinite subject–verb sequences from questions (e.g., *Does he run?*) as well as other double verb constructions in the input (e.g., *We saw the bear/him eating*, *Let Mummy help*). These sequences can serve as the basis for generating (ungrammatical) novel utterances with the same structure. Since these structures may include sequences that are not permissible as independent utterances in the adult grammar, this may give rise to Optional Infinitive errors. Children with DLD are thought to be particularly late to grasp the relation between nonfinite subject–verb sequences (e.g., *he run*) and the finiteness that is expressed earlier in the utterance (e.g., *does*) and will therefore continue to produce nonfinite subject–verb sequences for far longer. The CSI hypothesis is compatible with evidence suggesting that children with DLD have more difficulty processing long-distance dependencies (Hsu, Tomblin, & Christiansen, 2014; Purdy, Leonard, Weber-Fox, & Kaganovich, 2014). As outlined above, the fact that Spanish question formation differs from English question formation means that nonfinite subject–verb sequences are very rare compared to English, and thus are unlikely to act as a source of competition (or confusion) for children learning Spanish—even for children with DLD.

The amount of evidence in the input for English third-person singular inflection is further reduced by the fact that the English progressive is used far more frequently than its Spanish equivalent. Thus, Spanish speakers are more likely to produce an overtly inflected lexical verb (e.g., *Come* "*eats*") to describe an ongoing event than English speakers who are more likely to use a progressive (e.g., *He's eating*), where person and number are marked on the auxiliary. Thus, given the same amount of input, children learning Spanish hear both more overtly inflected forms, and a greater diversity of inflected forms than in English, where the bare form dominates the system, questions are a source of conflicting information, and the extensive use of progressives further reduces the amount of overt evidence for person and number inflection on lexical verbs.

1.2.3. The role of overt subjects

A final difference between Spanish and English is that, like most heavily inflected languages, Spanish is a pro-drop language, whereas English is an obligatory subject language. The pro-drop nature of Spanish has also been implicated in explaining the differential profile of English and Spanish children with DLD. As described earlier, according to the morphological richness account, children with DLD devote their attention to the most prevalent grammatical cues in the language they are learning. In a language like English, word order represents the most dominant grammatical cue, whereas verb inflections will be the main focus in a language with a rich inflection system such as Spanish.

In this paper, we will explore a related option. We hypothesize that children who are acquiring language attempt to associate the semantic cues that accompany an utterance with the linguistic elements that occur in the utterance. In the case of person–number cues and Spanish input, the sentential element that will be most closely associated with the person and number cues is the verb suffix. In most instances, Spanish utterances have no overt subject, and the verb suffix has a one-to-one relation with the subject (there is a separate suffix for every person–number combination). This means that the verb suffix is the only sentential element that reliably discriminates between the different person–number combinations. This is not the case in a language like English, where the same verb form is used for many person–number combinations, and the sentence-level element that most reliably discriminates the different person–number combinations is the overt subject (which often takes the form of a pronoun). Moreover, since the overt subject precedes the verb, it is not just the only element that reliably provides person–number information, it is also the first sentential element to do so. This may mean that when the child encounters the verb, she may be less inclined to process it for person–number information. However, it also means that when person–number cues are opaque and cannot easily be derived from the context, they are provided by the pronoun, which occurs before (i.e., at an earlier time) than the verb. To the extent that the verb is then processed for person–-number information, it requires the child to integrate the information provided by the earlier occurring pronoun with the verb suffix (that may or may not be present). In contrast, in Spanish, the semantics of person and number are most easily associated with the verb suffix, and when not recoverable, are provided at the same time as the verb, and may thus be more easily integrated.

This account can not only explain why typically developing children learning Spanish have less difficulty acquiring verb inflection than their English counterparts, but it may also explain the increased difficulty that children with DLD have in acquiring English verb inflection, because the process of integrating the pronoun and verb inflection may be particularly challenging, especially when their discrepant features must be reconciled (e.g., *she go* vs. *she goes*, both of which might be encountered).

In fact, it might be argued that all three aspects that make English verb inflection hard to learn involve aspects of sequential learning and may thus be particularly challenging for children with DLD. The impoverished nature of English verb inflection means not only that the bare form dominates the system, and hence that defaulting effects are likely to be more pronounced, but also that the semantics of person and number are expressed on a (pro)noun that precedes the verb. The process of integrating person–number semantics with verb inflection may thus be particularly challenging for children with weak language learning abilities. Moreover, the English process of question formation means that nonfinite verbs regularly follow third-person singular subjects. Children with reduced sequential learning abilities may be particularly slow to realize that these sequences are not permissible in isolation, but are instead licensed by the presence of a finite verb form that occurs earlier in the utterance. A sequential learning account of DLD may thus integrate defaulting errors with the CSI hypothesis and the morphological richness account.

In this paper, we investigate whether a sequential learning model can account for the differential patterns in the acquisition of verb inflection in both typically developing and language-impaired children acquiring English and Spanish. We train this model on input that reflects both the statistics and the structure of English and Spanish, and investigate how well the model is able to acquire the two systems of verb inflection. Our model attempts to predict the inflection present on a verb on the basis of the contents of an utterance as it unfolds over time. We conceptualize an utterance as a combination of contextually derived and sentence-level cues, the latter of which unfold sequentially (occur in consecutive time steps). A central feature of our simulations will be the manipulation of the model's ability to learn from information occurring in different time steps (i.e., earlier or later in sequences, as is the case with a verb suffix and the earlier cues to its occurrence). This manipulation is intended to reflect the differential sequential learning abilities of typically developing and language-impaired children and is expected to have large effects on the acquisition of English verb inflection, while leaving the acquisition of Spanish verb inflection relatively unaffected.

2. The learning model

The model that we will be using for our simulations is an extension of the Rescorla–Wagner (1972) error-driven model of associative learning that was specifically designed to account for sequential learning effects (Gureckis & Love, 2010). To explain its workings, we begin with its base, the Rescorla–Wagner model, which was traditionally used to explain data from animal learning, but has recently been applied to the learning of linguistic material by human children (Ramscar, Dye, & Klein, 2013; Ramscar, Dye, & McCauley, 2013), including effects relating to the sequential properties of language

(Arnon & Ramscar, 2012; Ramscar, Dye, Popick, & O'Donnell-McCarthy, 2011; Ramscar, Yarlett, Dye, Denny, & Thorpe, 2010).[1] Learning events within the Rescorla–Wagner model are conceptualized as a set of cues that are used to predict an outcome. The key assumptions behind the model are that the goal of learning is to use environmental information to reduce a learner's uncertainty about events, and that environmental cues compete for predictive strength. Every cue in the environment has a predictive association (or weight) with all possible outcomes that can be positive or negative (positive for outcomes that can be expected to occur, and negative for outcomes that can be expected not to occur). The associative strengths of cues are increased on learning trials where a cue and outcome co-occur (successful predictions), but are decreased on trials where a cue occurs and a predicted outcome fails to occur (prediction error). There is no change to weights associated with cues that do not occur. Because uncertainty is finite, and because cues can lose as well as gain associative strengths, learning is a competitive process that serves to discriminate the most informative cues in the environment (Ramscar et al., 2010).

A key characteristic of the Rescorla–Wagner model is that changes in associative strength are inversely proportional to the sum of the predictive value of all cues in the current trial. Thus, if the current set of cues is a good predictor of the outcome, weight changes will be small. Weight changes will be large if the current set of cues is not strongly associated with the current outcome. This means that weight changes tend to be larger early in training, and tend to decrease when the number of training trials increases. However, it also means that once a cue or set of cues has been well established as a predictor of an outcome, it will be difficult to associate novel cues with the outcome. Formally, the weight changes on a learning trial are governed by the following formula:

$$\Delta V_{ij}^{n+1} = \alpha_i \beta_j \left(\lambda_j - V_{\text{total}}\right),$$

where alpha and beta represent stimulus salience and learning rate, lambda the maximum associative value supported by a trial, and V_{total} the sum of all associative values between the current cue set and an outcome. The parameter lambda is set to a positive value (often 1) for an outcome that is present. Lambda is set to 0 for (predicted) outcomes that do not occur, and hence leads to the unlearning of incorrect predictions. Learning within the Rescorla–Wagner model is thus a dynamic process. Associations between cues and outcomes are continually adjusted to reflect their pattern of co-occurrences in the environment. Ultimately, this results in the matrix of weights between cues and outcomes reflecting the value of the various predictive relations supported by the environment.

Ramscar, Dye, and Klein (2013; see also Ramscar & Yarlett, 2007) have shown how the Rescorla–Wagner model can explain children's production of (English) plural overregularizations. Key to this model is that, in order to simulate object naming, it has to learn the appropriate set of semantic cues to each singular and plural noun form. Accordingly, the model is provided with a set of input cues $C_0, \ldots, C_x$ representing the various discriminable features of the set of objects to be labeled, and a context cue (by convention, C_0 is a context cue, and is assumed to represent the context in which learning takes place, see Danks, 2003).[2] As the model is then exposed to a representative distribution of English singular and plural nouns, it learns to associate the semantic cues with the noun forms based on the degree to which each cue is informative about each noun in context (where informativity is defined as minimizing predictive error).

When it comes to learning the cues to plural forms, the high frequency of regular plurals leads to a situation early in learning where the general association between plurality (a cue signifying that multiple items are present) and the frequent regular plural outcome (add -s to the noun root) tends to dominate the more specific cues that are associated with the less predictable forms of irregular plural nouns in the input (e.g., multiple mouse items in the case of *mice*). These over-general initial associations lead to a situation early in learning where the plural -s outcome tends to act as a default. However, as training on the distribution of nouns increases, the cue competition that is enforced by the learning algorithm causes the more general multiple items and context cues to lose value to the more specific cues, such that the model effectively learns to *ignore* the erroneous general cues in mouse contexts. This in turn causes the model to stop defaulting to the plural +*s* outcome, and its performance increasingly converges on the correct pattern of output given the input distribution.

The fact that the Rescorla–Wagner model can successfully account for the acquisition of (irregular) plurals, and successfully predicts detailed changes in the pattern of over-regularization errors produced by children (Ramscar, Dye, & Klein, 2013), suggests that it is a natural candidate for simulating the acquisition of verb inflection, where defaulting errors are also apparent. However, whereas the plural model just described deals with single word naming, the present study is concerned with the production of forms that occur in sequences, and the standard formulation of the model does not accommodate cue sets that unfold over more than one time step.

To remedy this, Gureckis and Love (2010) developed an extension of the Rescorla–Wagner model that incorporates a simple shift-register memory (see, e.g., Elman & Zipser, 1988; Hanson & Kegl, 1987) for events as they occur sequentially, enabling learning from cues that occur at different sequential time steps to be simulated in a principled manner. A key feature of the Gureckis–Love model is that, although it is similar to the Rescorla–Wagner rule in that it learns to associate all cues in all time steps with the outcome of a trial, the provision of memory registers enables memory for events that occur further back in time to decay (they have less predictive value because the model "forgets"), so that the influence on learning (weight updates) from earlier occurring cues in the model becomes *attenuated* relative to later occurring cues.

A learning trial consists of two phases. In the first phase, the model computes how well predicted each potential outcome is. Each outcome is associated with a detector or node that takes on a high activation value if the outcome is strongly predicted by the cues that have occurred in a trial. The activation of a detector is computed by taking the cues that occur in each time step and summing their associative weights to the outcome in question. The sum of all weights in a given time step is then multiplied by an attenuation factor, which gives greater weight to more recent time steps. The attenuation factor is described by the following formula:

$$\text{att} = 1/e^{\text{alpha} \times d}$$

The attenuation factor is controlled by a parameter alpha and d, the (temporal) distance between the cue and the outcome. The value of d reflects the sequential structure of a training trial. The value of d is larger[3] for cues that occur in early time steps (far from the outcome) and smaller for items that occur later (nearer the outcome). The shape of the attenuation curve is sigmoid (S-shaped). The parameter alpha controls the steepness of the sigmoid, and hence determines the relative contribution of the cues that occur in different time steps. For large values of alpha, the forgetting curve is steep, and only very recent events will have a meaningful influence on the model's predictions. For low levels of alpha, the forgetting curve is flatter and the influence of events that occurred further back in time will be larger.

After the attenuation factor is applied, the predictions for a given outcome from each time step are summed. This results in a single number for each potential outcome—the activation. For outcomes that are strongly predicted, the activation will be a large positive number. For outcomes that are disfavored, the activation will be a large negative number. Outcome activations are "squashed" through a sigmoid transform to result in a number between 0 and 1—the "output" for a given outcome.

In the second phase, the output for each detector or outcome is compared with the actual outcome for the trial and the predictive weights adjusted accordingly. In line with the original Rescorla–Wagner formulation, predictive weights from the cues in the trial to the outcome that actually occurred will be increased. Predictive weights from the current cue set to outcomes that did not occur will decrease. Weight changes are proportional to the discrepancy between the model's prediction and outcome. Weight changes will be larger when an outcome is strongly predicted and does not occur than when it is weakly predicted. Weight changes are subject to the same attenuation factor that weights the activations from a time step. Thus, weight changes are larger (and learning is faster) for cues from more recent time steps, and smaller for cues that occur further back in time. As discussed earlier, the relative weighting of the different time steps is controlled by the attenuation factor alpha. Alpha is thus a major determinant of the model's ability to learn sequential information, and hence a key candidate for simulating differences between children with DLD and typically developing children, and indeed the variable alpha is the main variable of interest in the simulations reported here. Weight changes are further subject to a learning rate, which, unlike alpha, has the same effect across all time steps and is not manipulated here. Weight changes to cues within a given time step are identical. Thus, the amount of learning that takes place during a given trial is determined by the sum of the predictions from all cues, and (disregarding attenuation) all weights are adjusted equally. However, since individual cues may participate in different trials, they come to differentially predict outcomes.

Here, we take the basic assumptions (and computations) from the Gureckis–Love model and apply them to the learning of information relevant to sequential, linguistic information. We conceptualize the task of learning verb inflection as one where the child attempts to predict the verb suffix (the outcome) on the basis of contextually derived as well as sentence-level semantic cues that unfold over time. Sentence-level cues are associated with different words in the utterance. In line with the Gureckis–Love model, we assume that sentence-level cues associated with words that occur early in the utterance have less predictive weight (their values are attenuated) than cues that occur nearer the outcome (the verb inflection), and their predictive relations will thus be harder to acquire.

3. Methods

Training data for the simulations reported in this paper were obtained from the child-directed speech to three English-speaking and two Spanish-speaking children. The English-speaking children (Anne, Aran, and Becky) are the first three (alphabetically) of the 12 children from the Manchester corpus (Theakston, Lieven, Pine, & Rowland, 2001). The Spanish-speaking children (Juan and Lucia) are the two children from the Orea–Pine corpus (Aguado-Orea & Pine, 2015). Both corpora are available from the CHILDES database (MacWhinney, 2000). The main focus was to extract verbal contexts that require a form of inflection. For English, this was done by searching the morphology (mor:) line of the transcript for present-tense main verbs that were preceded by a pronominal or nominal subject, and infinitives and progressives that were preceded by a pronominal or nominal subject and a present-tense modal or auxiliary verb (including contracted forms). The extracted sequences included finite declarative forms (e.g., *I go*; *Mummy goes*), modal constructions (e.g., *You can go*), questions (e.g., *Does he go? Can he go?*), as well as progressives (e.g., *He's going*; *Are you going?*). Imperatives were excluded, as were past-tense forms and constructions with perfect participles. We included double verb constructions (e.g., *Make it go*), and treated the initial verb as if it were a modal verb in a question, as in *Can it go?* (to reflect the fact that it takes the same position as a modal verb; we do not assume that it carries a similar meaning). We excluded infinitival constructions (e.g., *Going to eat*), but included instances of "going to" (but not "gonna") as a progressive main verb. We included Optional Infinitives that occurred in the input (e.g., *Anne do it*), and utterances with missing modals and auxiliary *do* forms (e.g., *Mummy help?*). Common and proper nouns were classified as third singular (or plural where appropriate) subjects. We inspected the source utterances for instances of third singular subjects followed by a bare form (in the absence of a modal verb) and excluded those constructions where the noun or pronoun was not the subject of the verb (e.g., W*hat box do you mean?*), or where it was part of a conjoined plural subject (e.g., *Mummy and Daddy go*). Training data were restricted to the 30 most frequent verbs (across the constructions described above). The verbs "*put*" and "*fit*" were not included in the 30 most frequent verbs as their bare form matches their past tense.

The analysis of the Spanish input was carried out in a similar manner, though the pro-drop nature of Spanish means that subjects were not required. Verbs that were marked as imperative were excluded. As in English, modal constructions (including the modal verbs *querer* [want], *poder* [can], *deber* [must], and *tener que* [must]) and progressives were included. Spanish questions were also included, but since the structure of Spanish questions does not differ from declaratives, they were not separately marked. As was the case for English, training data were restricted to the 30 most frequent verbs. The Spanish training set contained a total of 10,685 trials. Since the number of English trials was greater, the English training set was randomly sampled down to the size of the Spanish set. Unless otherwise noted, models were always shown the training set three times, for a total of approximately 32,000 trials.

For the purposes of the simulations, each trial was restricted to the (pro)noun, verb (and modal/auxiliary) sequence. That is, the rest of the phrase in which the sequence occurred was ignored. All modal (and auxiliary) verbs were represented using a single "modal" (or "auxiliary") marker. Likewise, (pro)nouns were replaced with the person–number cues they represent (*he/she/it/Mummy* → third-singular). Thus, training trials did not distinguish between different modal (or auxiliary) forms or gender/animacy markings; nor did they preserve the identity of common or proper nouns. Each word in a training sequence was considered to occur in a different time step, and the word order of declaratives and questions was maintained. Since contracted forms (e.g., *he's*, *you're*) combine the semantics of the pronoun and modal/auxiliary in one word, they were considered to occur in the same time step. The task of the model was to predict the verb inflection (i.e., to learn the contexts in which any given inflection occurs). For English, this could be one of three forms: a bare form (zero suffix), third singular -s, or a progressive -ing. For Spanish, this could be one of six present-tense forms (or a progressive or infinitive). A complicating factor for Spanish is that some verb inflections differ across the three conjugation classes (verbs ending in -ar, -er, -and -ir). The task of the model was to learn the appropriate inflection given a verb's class. However, in order for the model to discover the commonalities (and hence to generalize across the verbs in a given conjugation class), we provided the conjugation class as a separate cue. Training trials were right-aligned such that the verb inflection occurred in the last time step, and preceding materials at $t-1$, $t-2$, etc.[4] Table 1 shows the structure of sample training trials in English. The Spanish equivalents of the English trials are shown in Table 2.

It will be apparent from Tables 1 and 2 that English trials extend further back in time since the semantics of person and number are expressed on a (pro)noun that is absent in Spanish. The semantics of person and number in Spanish are provided on the verb. This

Table 1
Sample training trials for English

Gloss	$t-3$	$t-2$	$t-1$	Target
He runs	—	3-SG	Run	-S
We play	—	1-PL	Play	BARE
He can swim	3-SG	Modal	Swim	BARE
Does he run	Aux	3-SG	Run	BARE
I'm running	—	1-SG, Aux	Run	-ING
Is he eating	Aux	3-SG	Eat	-ING

Table 2
Training trials for Spanish equivalents of Table 1

Gloss	$t-2$	$t-1$	Target
Corre	—	Correr, -er, 3-SG	-E
Jugamos	—	Jugar, -ar, 1-PL	-AMOS
Puede nadar	Modal, 3-SG	Nadar, -ar	-AR
¿Corre?	—	Correr, -er, 3-SG	-E
Estoy corriendo	1-SG, Aux	Correr, -er	-IENDO
Esta comiendo	3-SG, Aux	Comer, -er	-IENDO

suggests that it will probably be easier for the model to successfully learn to associate the semantics of person and number with the verb suffix. However, it is also true that Spanish has more distinct forms, as well as different conjugation classes, which in turn may make Spanish more difficult to acquire. It is also apparent from Table 1 that the English trials "*He runs*" and "*Does he run?*" have a different target (-S and BARE respectively), despite sharing the semantics of third singular at time $t-2$. The trial "*Does he run?*" thus, quite literally, acts as a "competing source of input" for "*He runs*."[5] This competition is absent in Spanish. The two constructions differ in intonation only, and as a result the learning trials (and targets) are identical.

Not shown (for readability) in Tables 1 and 2 is the context cue. In line with the Ramscar, Dye, and Klein (2013) model of the English plural, a context cue is provided in all time steps on all trials. Since this cue (which can be thought of as representing the task context) is always present, it may initially be associated with (i.e., be the best predictor of) the most frequent response, and hence lead to defaulting effects, which are likely to be larger for English, where the bare form dominates the system.

3.1. Training methods

Training took place by showing the model the input corpus a total of three times (or around 32,000 trials when trained on the full corpus). The learning rate (eta) was fixed (at 0.5) throughout. Weights were initialized to random values between −1.0 and 1.0. Target outputs were collected every 100 trials. All models were run 10 times with different initial random weights, and target outputs were averaged over these 10 runs. The central variable of interest was the attenuation factor alpha, which controls the model's ability to associate events that occur in different time steps. We ran models using varying levels of alpha to investigate how this affects the model's ability to learn the English and Spanish system of verb inflection. Models trained at low values of alpha reflect the performance of typically developing children, while models trained at high values of alpha reflect how the learning of verb inflection is affected by reduced sequential learning, which is characteristic of DLD.

3.2. The (pro)noun step parameter

Thus far we have assumed that the obligatory subject nature of English means that person and number cues are provided with the (pro)noun, and hence in a different time step than the main verb, while the pro-drop nature of Spanish means that person and number cues are provided with the main verb. If English-speaking children learn to associate person and number with the (pro)noun rather than directly with the verb inflection, they should be slower to acquire verb inflection. Moreover, we would expect that models that receive person and number cues in an earlier time step should show larger effects of manipulations of the alpha parameter (i.e., be more susceptible to reduced sequential learning). This manipulation, which we shall refer to as the *(pro)noun time step*, has close parallels with the morphological richness account which states that children acquiring richly inflected (i.e., pro-drop) languages pay closer attention to the verb inflection and hence show less of a deficit in DLD. However, implementing the morphological richness account in terms of sequential learning also has the potential to unify it with the CSI hypothesis, as well as defaulting accounts, in terms of a single processing factor which has been shown to be affected in DLD. On the other hand, since it could be argued that the semantics of person and number are also available when an English child encounters the main verb, we also ran English simulations where we provided the semantics of person and number on the words that followed the (pro)noun as well as on the (pro)noun itself. This manipulation should make the English simulations more like the Spanish simulations, and less sensitive to manipulations of the attenuation parameter. Note, however, that this also makes it easier to associate third singular subjects with the bare forms that accompany them in questions and declarative modals.[6]

4. Simulations

A first set of simulations was aimed at investigating whether the model could successfully simulate the early acquisition of Spanish relative to English verb inflection that is evident in typically developing children. Models for both languages were run with an attenuation (alpha) of 0.4, and a learning rate of 0.5, and trained on an equally large input set that reflects the statistics of the target language. Results of these simulations are shown in Fig. 1a (English) and 1b (Spanish, collapsed across the three conjugation classes). Plotted in Fig. 1 are the outputs for the target suffix in a finite present-tense context. Outputs range from 0 to 1, with values below 0.5 indicating that the target is dis-preferred, and values above 0.5 indicating that the target is preferred. Low output values thus indicate that the model (or child) is likely to select an alternative (incorrect) form, while high values indicate that the model (or child) is likely to select the correct (target) form.

For English, we probed the third singular context (we do not show other present-tense contexts, since the target form is the bare form which acts as a default). For Spanish, we probed all person–number contexts, except the second plural, which is exceedingly rare in the input, and thus is not acquired by the model. Results are averaged over the 30 verbs in the training set. Fig. 1 shows that the English models are slow to acquire the third-person singular, at least compared to the singular Spanish forms, whose outputs exceed 0.8 after as few as 5,000 training trials. Learning of the Spanish plural forms is slower. In the case of first-person plural, this reflects the model's poor performance on

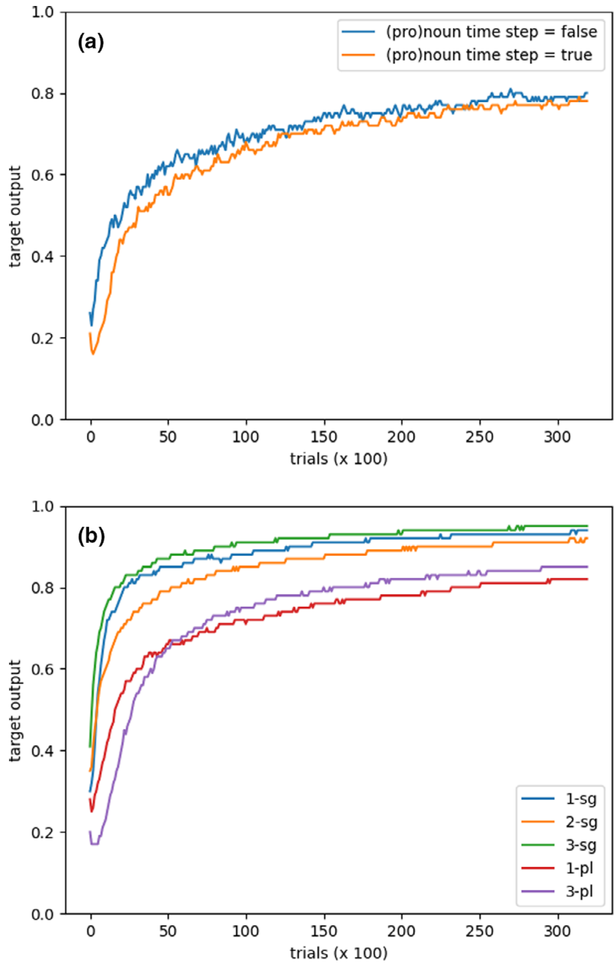

Fig. 1. English (a) and Spanish (b) models at an attenuation (alpha) of 0.4. English models show output for third-person singular contexts, with the (pro)noun time step either absent (false) or present (true). Spanish models show output for all person-number contexts (1-sg = first singular, 2-sg = second singular, etc.), except second plural.

verbs ending in -imos. These verbs are rare in the input, and the model only manages an output of around 0.4 at the end of training. This is in contrast to verbs ending in -amos and -emos that have outputs near 0.8 at the end of training. This disparity, which is not apparent in the children tested by Bedore and Leonard (2001), may be specific to our training set. Learning of the third plural is also slow, which is consistent with data reported by Aguado-Orea and Pine (2015).

Fig. 1a (English) also shows a (small) effect of the (pro)noun time step parameter. As expected, learning is faster when person and number cues are provided on both the pronoun and the main verb (as they are in Spanish), and thus more easily associated with the -s suffix. However, it should be stressed that the effect of the (pro)noun time step is small, and that even in the absence of the (pro)noun time step, the model is slow to learn English third singular, at least when compared to Spanish singular forms. The reason why the English model is slow, even when person–number information is provided with the verb, is that much of the input consists of questions and progressives and hence that third-person singular subjects are frequently associated with suffixes other than third-person singular -s (e.g., *Is he going*, *Does he go*). In fact, one of the challenges for the model is to learn that these other suffixes are not associated with the third singular subject, but with the modal or auxiliary verb that precedes it, making these associations harder to acquire. That is, English models need to learn to discriminate the contexts in which third-person singular subjects predict an -s, -ing, or bare suffix, and this problem is

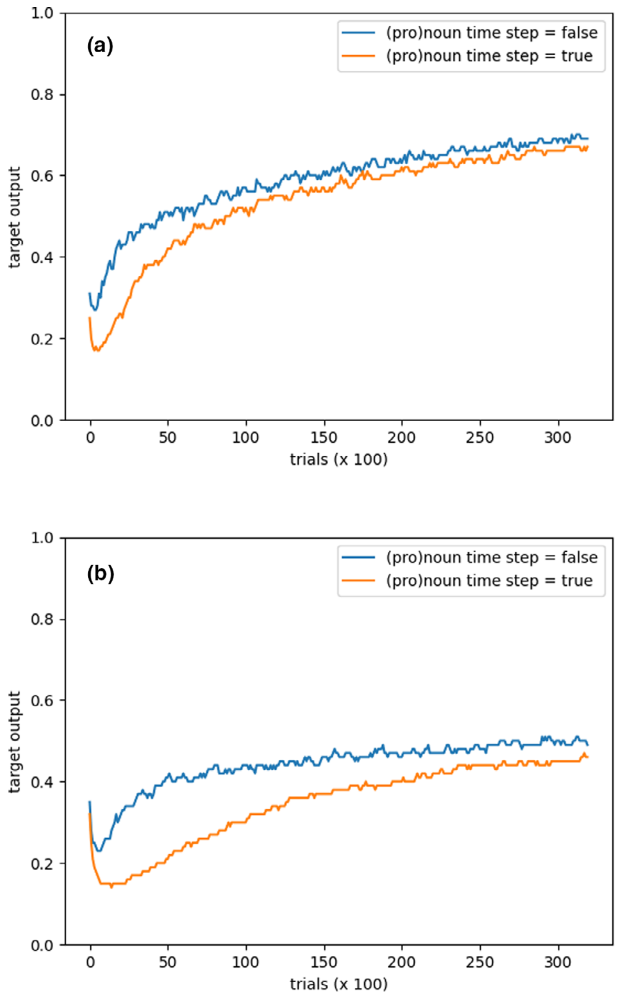

Fig. 2. English models with attenuation (alpha) of 0.6 (a) and 0.9 (b).

greatly reduced in Spanish. This results in slower acquisition of English third singular—even in the absence of the (pro)noun time step.

The simulations reported in Fig. 1 employed attenuation levels that might reflect typically developing children's ability to learn sequential information. The second set of simulations investigated the model's performance at higher levels of attenuation, which might reflect the reduced sequential learning abilities of children with DLD. Fig. 2 plots the model's performance on the English third-person singular at attenuation levels of 0.6 (Fig. 2a) and 0.9 (Fig. 2b). As can be seen in Fig. 2, increasing attenuation results in markedly worse performance. It is also apparent that the effect of the (pro)noun time step manipulation is larger at higher attenuation levels. Neither effect is surprising. For models that receive the person and number cues only on the (pro)noun, it becomes harder to associate these cues with the -s suffix, which occurs much later. However, high attenuation also degrades performance, when subject information is provided with the verb. As noted earlier, this is because the model needs to learn that bare forms and progressives in third-person singular contexts are not associated with the third-person singular subject, but with modal and auxiliary forms that occur earlier than the main verb. This association is harder to learn at high levels of attenuation. Taken together, the English simulations thus provide support for Leonard and Deevy's (2011) CSI hypothesis, which states that English children fail to grasp the relations between subject–nonfinite verb sequences and the finite verb forms that precede them. However, the simulations also relate this failure directly to the reduced sequential learning abilities of children with DLD.

Fig. 3 shows the performance of the Spanish models at attenuations of 0.6 and 0.9. While some degradation in performance is apparent (in particular for the lower frequency plural forms), the effects of increased attenuation are considerably smaller than in models trained on English. It is easy to see why this is the case. First, Spanish models are always presented with person and number cues together with the verb, and the effects of attenuation are thus reduced relative to the English simulations where they may be presented with the (pro)noun. Second, the relative lack of competition from questions and progressives (which are rare in Spanish) means that, unlike models trained on English, they have less need to associate these with the modals and auxiliaries that occur in earlier time steps. This of course does not mean that Spanish children with DLD have better sequential learning abilities. Rather, it means that children who are poor at sequential learning are at less of a disadvantage (at least when it comes to learning verb inflection) when they are learning Spanish than when they are learning English. However, since learning sequential relations can be challenging even for typically developing children, it also means that typically developing children will be quicker to acquire Spanish compared to English verb inflection.

It may be worth stressing at this point that there is no clear answer to the question of what level of attenuation best characterizes "typical development." The simulations reported in Fig. 1 show faster learning of Spanish singular forms than English third singular, while all Spanish forms are learned faster at the higher attenuation levels in Fig. 3. It may well be the case that the behavioral data are best described by an attenuation level higher than 0.4. However, the main point to be taken from these simulations is that the

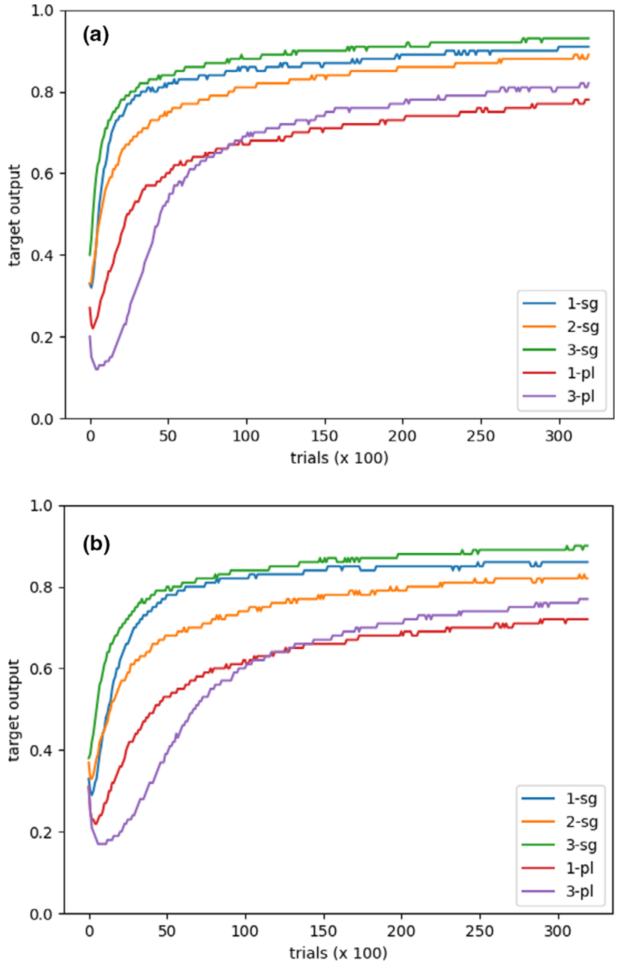

Fig. 3. Spanish models at attenuation (alpha) of 0.6 (a) and 0.9 (b).

effects of increasing attenuation are larger in English than in Spanish, and the precise values that may reflect typical and impaired performance are somewhat arbitrary. As an illustration, consider Fig. 4, which shows an English model at an attenuation of 0.9, trained on 24 (i.e., ~250,000 trials) rather than three exposures to the training set. This model manages to reach a similar level of performance to the models trained at lower attenuation levels, but it requires far more input (eight times more than the model trained at an attenuation of 0.4 or five times more than the model trained at an attenuation of 0.6). English models with high attenuation are thus considerably slower than low attenuation models, and these effects are markedly reduced in the Spanish models. Sequential learning can thus explain both the slow acquisition of inflection in English compared to Spanish in typically developing children, and the delayed acquisition shown by English children with DLD (and the relative lack of such an effect in Spanish).

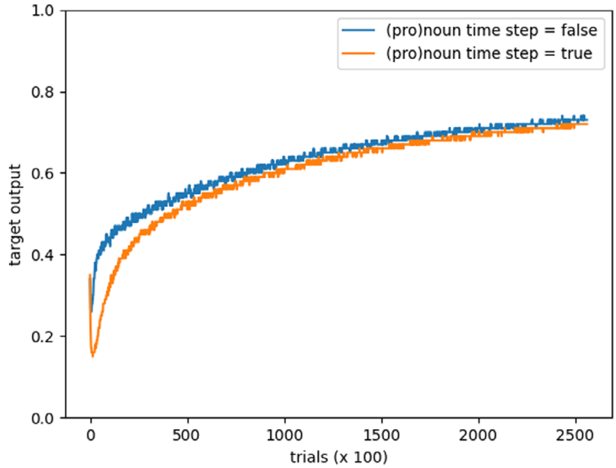

Fig. 4. English model at an attenuation of 0.9 trained on 250,000 trials.

A final set of simulations was aimed at teasing apart the role of English questions and other modal constructions and the fact that the bare form dominates the present-tense inflectional system. To this end, we removed all compound constructions (questions, progressives, and modal constructions) from the English input, leaving only simple finite constructions (i.e., *I go*, *You go*, *He goes*, etc.). Compound constructions contain no overtly inflected main verbs, and at best provide little or even (in the case of questions) conflicting evidence for inflection. Yet compound constructions make up nearly 65% of the English training set. In contrast, they make up around 10% of the Spanish training set, thus underlining the fact that, given a training set of equal size, Spanish input provides far more evidence for inflection than English input.

Fig. 5 shows the results of these simulations at three different levels of attenuation, with and without a (pro)noun time step. As can be seen in Fig. 5a (no (pro)noun time step), the English model trained without compound constructions looks remarkably like the Spanish models—even at high levels of attenuation, thus showing that compound constructions (in particular questions) are a major source of competition for learning the third-person singular. However, as shown in Fig. 5b, the model's performance is significantly reduced when the (pro)noun time step is employed. Inspection of Table 1 (English training trials) reveals why this has a large effect on the simulations. The model's task is to predict the inflection based on the cues at time $t-2$ (the subject (pro)-noun) and $t-1$ (the verb, as well as the context cue which is present at both time steps [but not shown in Table 1]). Since the subject (pro)noun is only present at $t-2$, the model will, in the early stages of training, only have a weak association between the (pro)noun and inflection, and predict the inflection on the basis of the context cue and verb which occur closer to the inflection. The best prediction in the early stages will thus be the form that is most frequent overall (or most frequent for the verb in question). This will invariably be the bare (default) form. As the model sees more

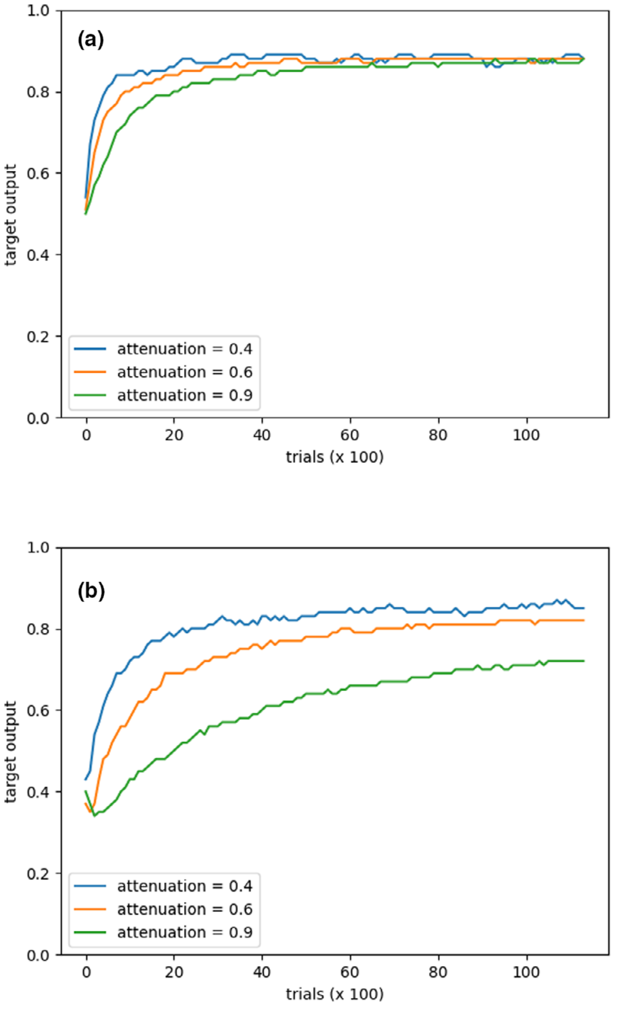

Fig. 5. English models trained on finite forms only, without (a) and with (pro)noun time step (b).

input, it becomes better able to associate the (pro)nouns at $t-2$ with the inflection and defaulting errors disappear. In the absence of a (pro)noun time step (Fig. 5a), the person–number information is provided together with the verb, and it has more predictive power. Defaulting errors disappear much more quickly as a result. These simulations thus suggest that, while the pronoun time step may not be necessary to explain the slow acquisition of English compared to Spanish verb inflection, it has similar effects to the inclusion of compound constructions. It thus seems that the combination of overt subjects (with impoverished morphology) and the high number of compound constructions in English input may be particularly challenging for children with reduced sequential learning abilities.

5. General discussion

The simulations reported here show that an error-driven sequential learning model can account for the pattern of verb acquisition in Spanish and English in both typically developing and language-impaired children. The model is slow to acquire English compared to Spanish verb inflection, and manipulations of the model's ability to learn sequential information have small effects in Spanish and large effects in English. Differences in the structure and statistics of the two languages mean that poor sequential learning abilities have far greater effects on the acquisition of verb inflection in English compared to Spanish. We identified three aspects that may make English verb inflection particularly challenging for children with poor sequential learning abilities.

First, the extensive use of progressives and the relative lack of overtly inflected forms in English mean that defaulting effects are more pronounced, and likely to persist for longer in children with poor sequential learning abilities. Second, the English process of question formation means that third singular subjects are regularly followed by nonfinite verbs. Children learning English may struggle to relate these sequences to the finite verb forms that precede them, and these effects may be more pronounced for children with DLD. Finally, the obligatory subject nature of English means that the semantics of person and number are expressed on the (pro)noun, and children with DLD may be particularly slow to integrate this with the (third singular) verb inflection. Our simulations showed not only that all three factors have a negative impact on the model's ability to learn the English third person singular inflection, but also that this impact is largest when the model's ability to learn sequences is most limited. Thus, the model was quickest to learn the third-person singular when questions and other modal constructions were removed from the input, and subject information was provided with the verb. Both the inclusion of questions and modals and the inclusion of the pronoun time step affected the model's performance, but these effects were largest at high attenuation levels.

Taken together, the simulation results suggest that a relatively simple error-driven model of sequential learning can account not only for the differences in the acquisition of verb inflection between typically developing children learning Spanish and English, but also for the profiles of children with DLD. In doing so, it integrates the morphological richness account, the CSI hypothesis, and the defaulting account of verb inflection in one single model that is (largely) controlled by a single parameter: children's ability to learn sequential information. This ability interacts with both the statistics and the structure of the input language to result in the different profiles of typically developing and language-impaired performance in English and Spanish.

We view the model's ability to unify the morphological richness, defaulting, and CSI accounts as an important step forward. These accounts have been treated as separate proposals, each handling a slightly different aspect of verb inflection difficulty. Furthermore, each has been based on assumptions about how input could, in principle, affect verb inflection, but none has been put to the test with input from naturally occurring adult–child interactions. The present study shows that differences in the structure and statistics of English and Spanish, in interaction with a relatively simple learning parameter, are sufficient to explain the differential patterns of acquisition of verb inflection in both typically developing and language-impaired children.

We believe this is an important finding for two reasons. First, showing that the structure and statistics of languages are sufficiently different is important because these factors are often poorly understood, and they can interact with learning mechanisms in unforeseen ways. Second, and relatedly, we have shown that all three accounts follow naturally from a sequential learning account—something which we suspect few readers would have predicted a priori.

At the same time, these results come with two important caveats. First, as argued in Section 1, sequential learning is unlikely to be a unitary factor—but is instead an ability that is dependent on a range of cognitive factors. Children with DLD may indeed be affected by a range of impairments, which, due to the sequential nature of language, may result in a common outcome, which may be subtly different depending on the specific deficit(s). Second, we have simplified the learning task that children face considerably. We have restricted the training set to sequences of (pro)nouns, modal/auxiliary and main verbs, right-aligned the input, provided the Spanish models with conjugation classes, and ignored the identity of modals, as well as gender and animacy. However, a model that did full justice to these factors would be considerably more complex, and thus considerably less easy to interrogate and understand than our model. Thus, our model simplifies both the learning task and the learning mechanism for the sake of increased transparency. However, in doing so, it provides us with important insights into the way in which the structure and statistics of English and Spanish are likely to interact with sequential learning ability to explain differences in the ease with which both typically developing and language impaired children acquire verb inflection in the two languages.

Along with simplifying the model, we have also added the detail of the (pro)noun time step. Given the contributions of defaulting and questions, the importance of the (pro)noun time step may not be obvious. After all, Fig. 2 shows clear effects of attenuation even when person–number information is provided on the verb, and it could be argued that the (pro)noun time step just "makes matters worse." There are, however, good reasons to assume that the (pro)noun time step reflects a fundamental property of obligatory subject languages that poses problems for children with DLD. The main reason is that problems with verb inflection have been reported in children with DLD in (obligatory subject) languages other than English. Languages like Dutch and German, for instance, employ more present-tense inflected forms than English, and thus sit in between Spanish and English in terms of the complexity of the paradigm. Moreover, since these languages use main verb inversion for question formation, this means that the amount of evidence for verb inflection is far greater (more like Spanish) than in English, and hence that the performance of children with DLD should be much improved compared to English. Problems with verb inflection in Dutch and German children with DLD, however, are well documented (Blom, de Jong, Orgassa, Baker, & Weerman, 2013; Hasselaar, 2014; Rice et al., 1997), though the exact profile may differ from English. The obvious commonality that German and Dutch share with English (and not with Spanish) is that they are obligatory subject languages, and hence that the semantics of person and number are expressed on the (pro)noun and thus in a different time step than in Spanish.[7] Thus, while the (pro)noun time step may not be strictly necessary to explain the differences between English and Spanish, it has the potential to explain differences between pro-drop and obligatory subject languages other than English.

Secondly, the (pro)noun time step has considerable overlap with the morphological richness account (indeed, the predictions of the two accounts are hard to distinguish). According to the morphological richness account, children will pay attention to those aspects of the grammar that mark the important distinctions for the language, and will thus pay more attention to verb suffixes in pro-drop languages. Such an account will arise naturally if one assumes that the way in which children learn causes them to associate the semantics of person and number with the first sentential element that uniquely defines it. This means that Spanish children will pay attention to the suffix, and English children to the subject (pro)noun. The semantics of person and number may become associated with the (pro)noun, which then needs to be integrated with the verb suffix. These problems may be compounded by the fact that pronouns are free-standing, unstressed elements that are vulnerable to omission in children's speech (Bloom, 1990; Gerken, 1991), a problem that may be more pronounced in DLD. Intriguingly, data from Spanish and Italian are consistent with such an account: One area where children with DLD in these languages struggle is that of preverbal object clitics which share many (prosodic) features with subject pronouns (Dispaldro, Leonard, & Deevy, 2013). Further support for the privileged status of suffixes relative to free-standing elements comes from the acquisition of grammatical case. Children generally make few errors in languages that express grammatical case as a noun suffix (e.g., Turkish, Aksu-Koç & Slobin, 1985). However, the acquisition of German case, which is expressed on the determiner, has been reported to be error-prone and protracted (Szagun, 2004). Case-marking has been shown to be affected in German children with DLD (Eissenbeiss, Barthke, & Clahsen, 2006; Hasselaar, 2014), though it is unclear whether problems with case-marking extend beyond what might be expected given these children's overall language abilities.

Taken together, these considerations suggest that, rather than being a convenient device for degrading the English model's performance, the (pro)noun time step may reflect a fundamental property of obligatory subject languages that makes verb inflection difficult to acquire for children with reduced sequential learning abilities. However, the fact that the (pro)noun time step exacerbates defaulting effects (which reflect the dominance of the English bare form) as well as the negative effects of English questions in the input suggests that English may be particularly challenging for children with DLD. This obviously does not mean that individuals with poor sequential learning abilities in other languages are unaffected. In fact, the simulations reported here suggest that Spanish children with DLD will have difficulties acquiring the low-frequency parts of the system and are likely to instead produce as a default the high-frequency third singular form which has been argued to act as an OI equivalent (Grinstead et al., 2013). The nature of defaulting effects can also vary within as well as across languages. Thus, the SOV-V2 nature of Dutch and German means that nonfinite forms occur in utterance-final position while finite forms occur in second position. Freudenthal, Pine, Jones, and Gobet (2015b) investigate the distribution of verb forms on a verb-by-verb basis, and show that in Dutch, verbs occurring in utterance-final position overwhelmingly occur in nonfinite form, while the stem[8] or third singular is the most frequent form when considering complete utterances. Freudenthal et al. argue that the nature of the default may change developmentally (as children's representations of the input become more complete/longer), consistent with the suggestion that there is not one specific profile that describes verb inflection errors in Dutch DLD (Blom et al., 2013).

The fact that the nature of verb inflection errors in DLD can vary both across and within languages obviously presents a major obstacle to the identification of the causes underlying DLD. However, it also highlights the strength of using computational modeling to investigate how learning mechanisms may interact with the structure and statistics of the input to shape children's language acquisition. Thus, we have been able to show that, despite the fact that the Spanish present-tense paradigm is arguably more complex than the English paradigm, Spanish input actually provides far more evidence for inflection, and the paradigm is thus easier to learn. Additionally, we have been able to study the effects of the (pro)noun time step, questions, and defaulting in isolation, and show that all three factors conspire to make the English third-person singular particularly hard to learn. Finally, we have shown that these effects are amplified under conditions of reduced sequential learning, suggesting that a sequential learning deficit may underlie the cross-linguistic pattern of verb-marking in children with DLD.

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Notes

1. It is worth noting that when the Rescorla–Wagner rule is simplified by the removal of its saliency parameters—as in the foregoing examples and in most other instances of its use in modeling human cognition—the resultant learning algorithm is equivalent to the delta rule defined by Widrow and Hoff (1960; see Stone, 1987).
2. The context cue is also important to correctly implementing the model: As in other delta-rule models, learning in the Rescorla–Wagner model asymptotes at a level that minimizes the sum-of-squares prediction error for a set of outcomes over a set of observed cue sets, and the context cue serves a function that can be likened to that of the intercept term in a regression model, in that it serves to ensure that the mean of these errors is zero.

3. For the current simulations, the value of d simply reflects the time step in which a cue occurs and ranges from 1 (most recent) to 3 (most distant).
4. Note that, since time steps are independent, the model has separate representation for *He can go*, and *Can he go*, which have no overlap at times $t - 2$ and $t - 1$.
5. Note that phrases like "*He's running*" also have a third singular form at time $t - 2$, and hence also act as competing forms for the third singular.
6. Since the subject in a declarative modal (e.g., *He can go*) occurs at a different time ($t - 3$) than in a simple declarative (e.g., *He goes*, $t - 2$), it actually provides limited competition when person and number cues are provided on the pronoun. However, providing these cues on both pronoun and main verb makes declarative modals direct competitors for third singular forms, and may thus make them harder to learn.
7. Though main verb inversion in question formation means that subjects may occur after verbs.
8. In Dutch, the stem is used as the first singular form in declaratives and questions as well as the second singular in questions (but not declaratives).

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